Tidal effects on scalar cloud (numerical simulation)

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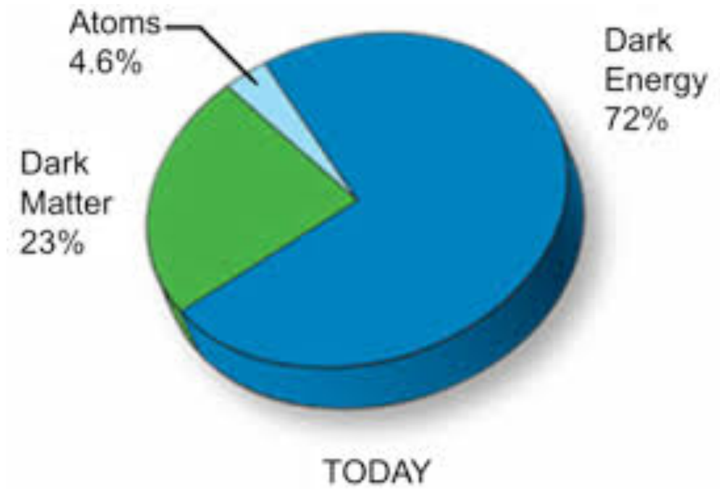
Light scalar field



Energy components

Dark Matter

- QCD axion
- string axion
- PBH et al

Dark Energy

- Cosmological constant
- Modified gravity
  - Scalar tensor theory
  - F(R) gravity
  - massive gravity et al

➡ Several models predict light scalar field.

Superradiant clouds

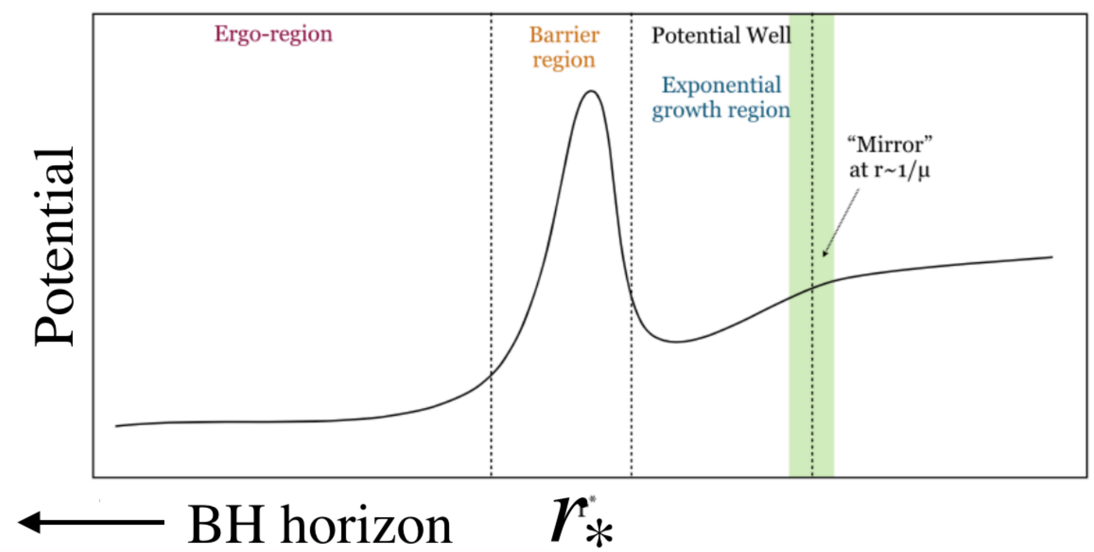
- Supperradiance

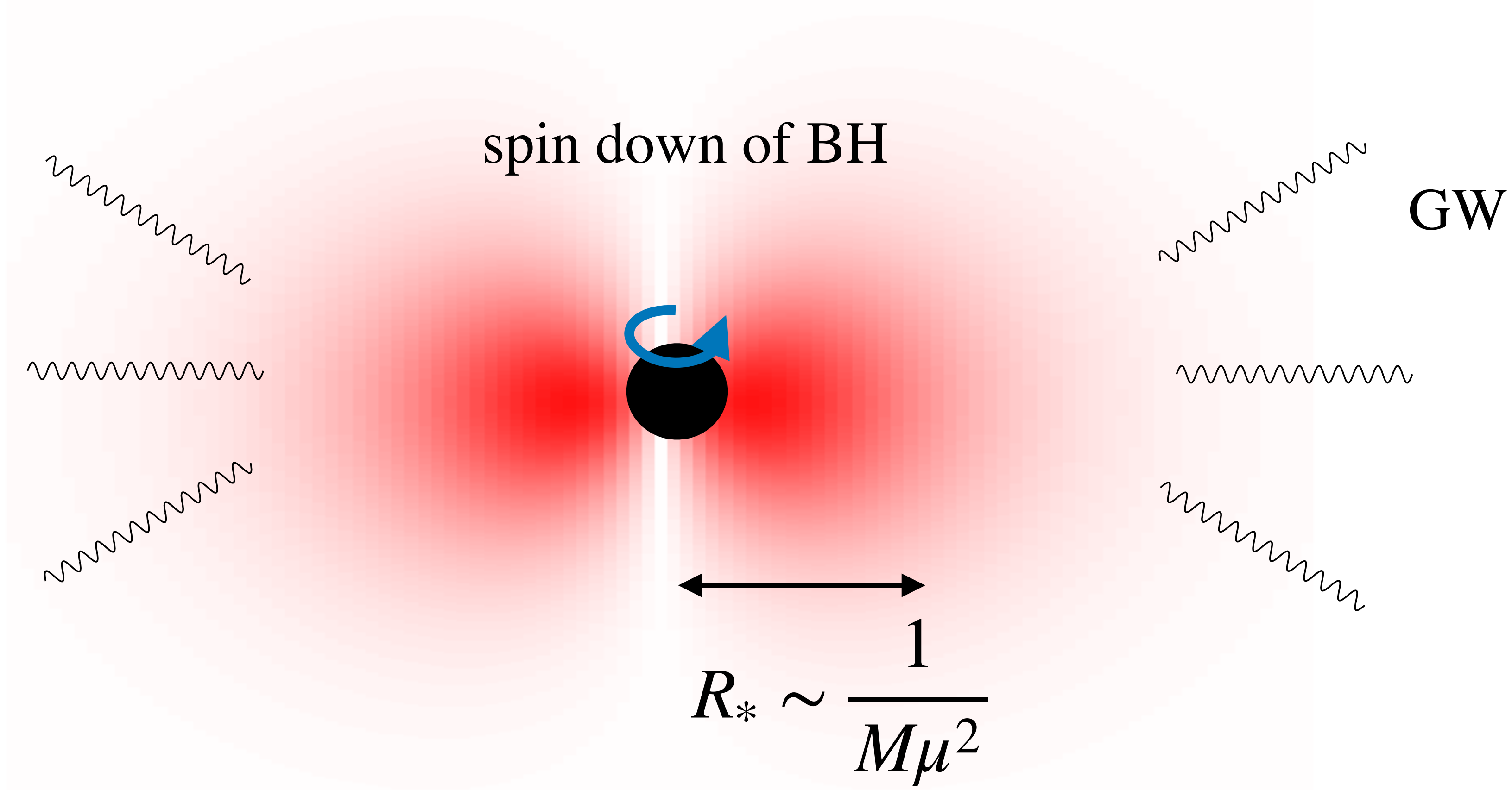
$$\Phi(x) = e^{-\omega t} e^{im\phi} S_{lm}(\theta) R_{lm}(r)$$

$$\Rightarrow \quad \mathrm{Re}(\omega) < m\Omega_{\mathrm{H}} = \frac{ma}{2Mr_+}$$

$$\tau \sim 100\tilde{a} \left(\frac{10^6 M_\odot}{M} \right)^8 \left(\frac{10^{-16}\mathrm{eV}}{\mu} \right)^9 \mathrm{sec}$$

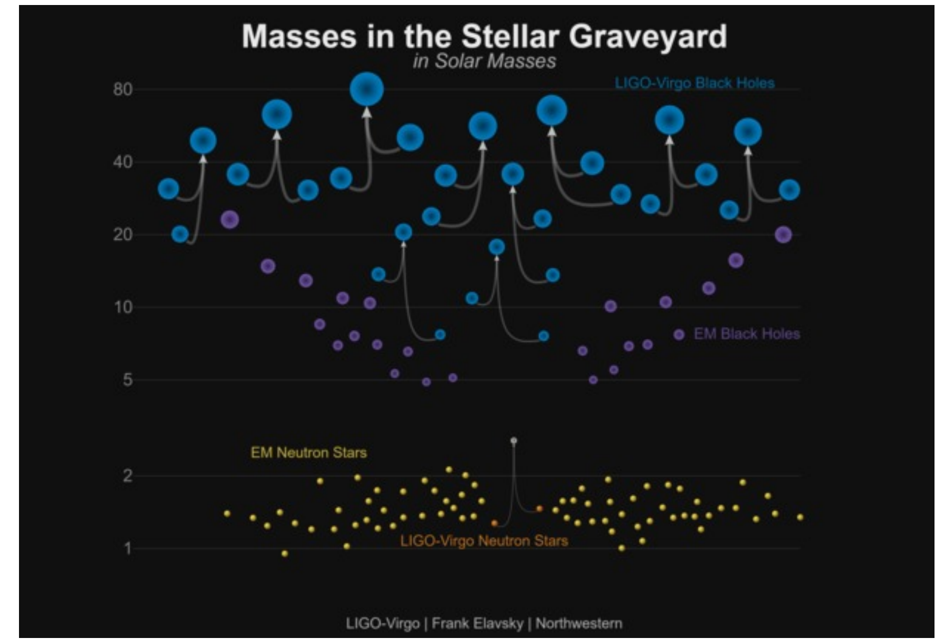
- Scalar cloud

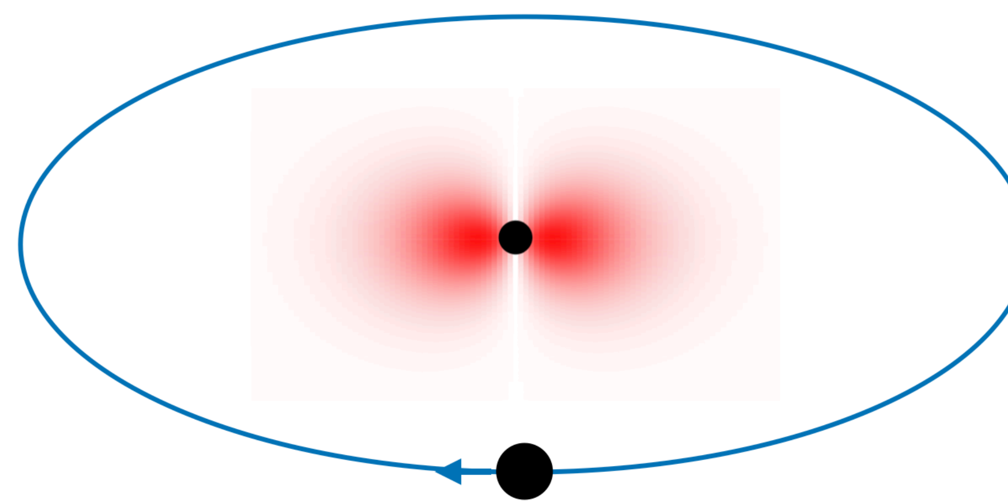




Black Hole has a companion.

- There are a lot of BH binaries in our Universe.
- Sgr A* and Cygnus X1 have companion stars.
- Scalar cloud around BH with companion star
    - Scalar cloud feels a tidal force.
    - Does tidal force change the dynamics of scalar cloud ?
    - Is scalar cloud disrupted ?





Previous work

$$V(r) = \frac{\alpha}{r}$$

- Mode mixing (D.Baumann et al PRD99,044001, E.Berti et al PRD99,104039)
  - single BH
    - $(\Box - \mu^2)\Phi = 0$ ➡ $i\partial_t \Psi = \left(-\frac{1}{2\mu^2}\nabla^2 + V(r)\right)\Psi$ ➡ $\begin{cases} |n, l, m> \\ \omega_{n,l,m} \end{cases}$

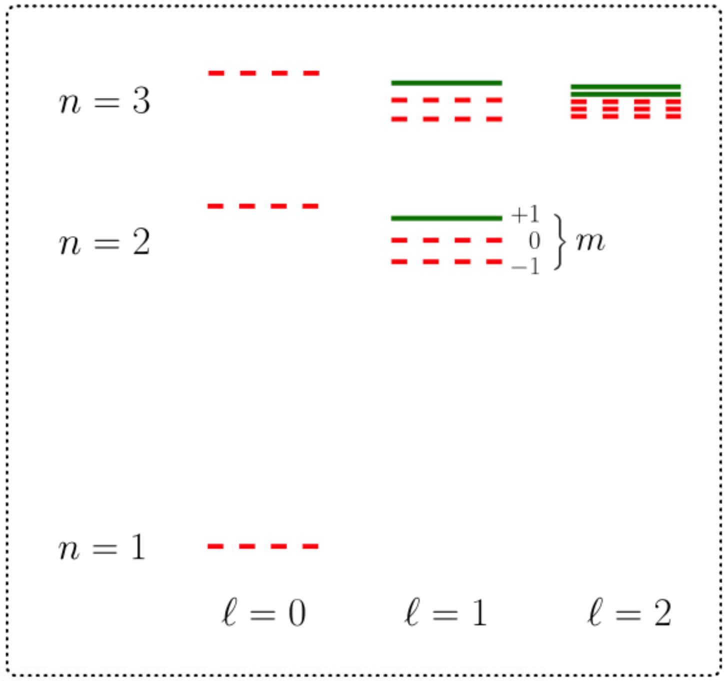
      $\begin{cases} M/r \ll 1 \\ \text{non-relativistic limit} \end{cases}$

      cf : QM of Hydrogen atom

    - higher order correction

$$\Delta\omega_{nlm} = \mu\left(-\frac{\alpha^4}{8n^4} + \frac{(2l - 3n + 1)\alpha^4}{n^4(l + 1/2)} + \frac{2\tilde{a}m\alpha^5}{n^3 l(l + 1/2)(l + 1)}\right)$$

    - $\mathrm{Im}(\omega_{nlm}) \propto m\Omega_H - \omega$
      - decaying mode $\mathrm{Im}(\omega^{(d)}_{nlm}) > 0$
      - growing mode $\mathrm{Im}(\omega^{(g)}_{nlm}) < 0$



Tidal effect on the cloud

$$i\partial_t \Psi = \left(-\frac{1}{2\mu^2}\nabla^2 + V(r)\right)\Psi$$

- Binary BH
  - The tidal effect deforms the potential.

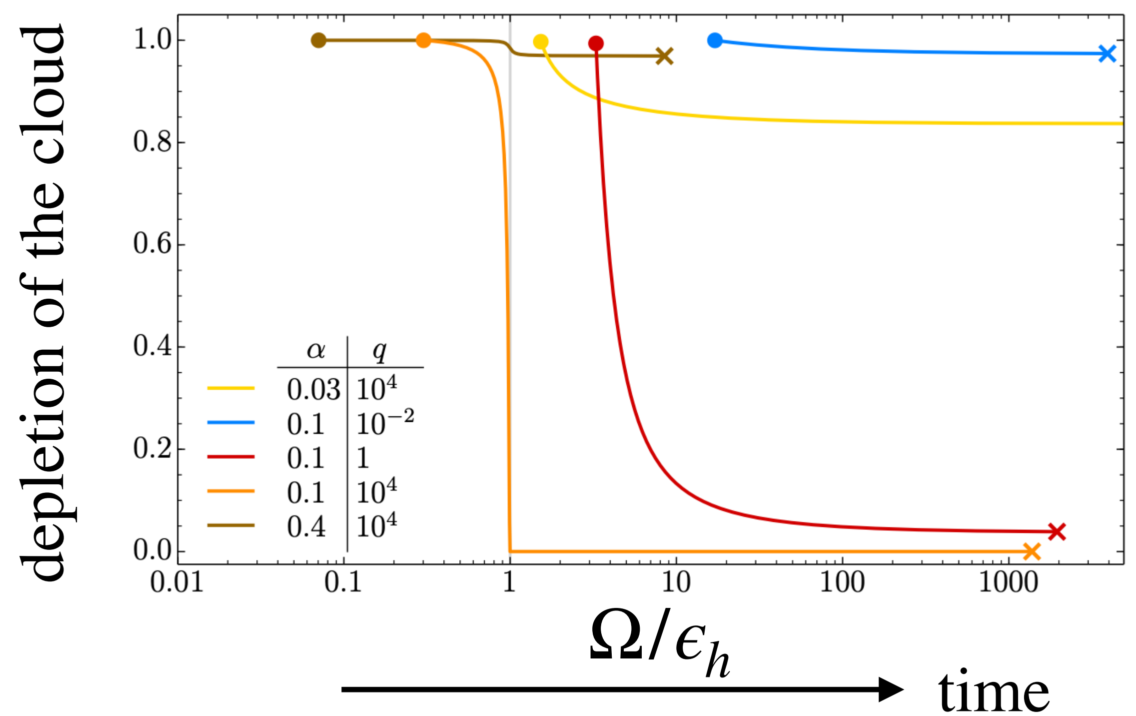
$$V(r) \to V(r) + \underline{\delta V(t, r, \theta, \phi)}$$

cf : Perturbation theory in QM

  - mode mixing

$$< n, l, m \,|\, \delta V \,|\, n', l', m' > \neq 0$$

  - Growing mode is coupled with decaying mode.

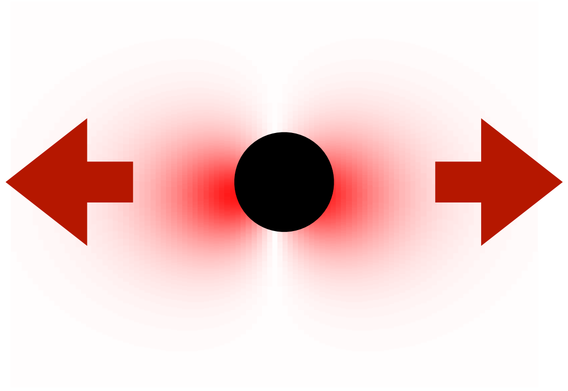


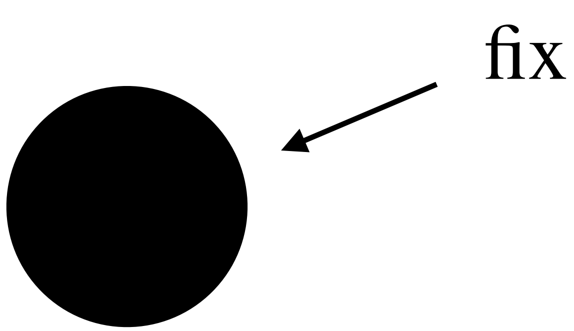
What we want to do

- Previous works : perturbation theory of QM
  - mode mixing between decaying and growing mode
  - depletion of the cloud
- Questions
  - What happens beyond perturbation theory ?
  - Is the cloud disrupted due to the strong tidal force ?

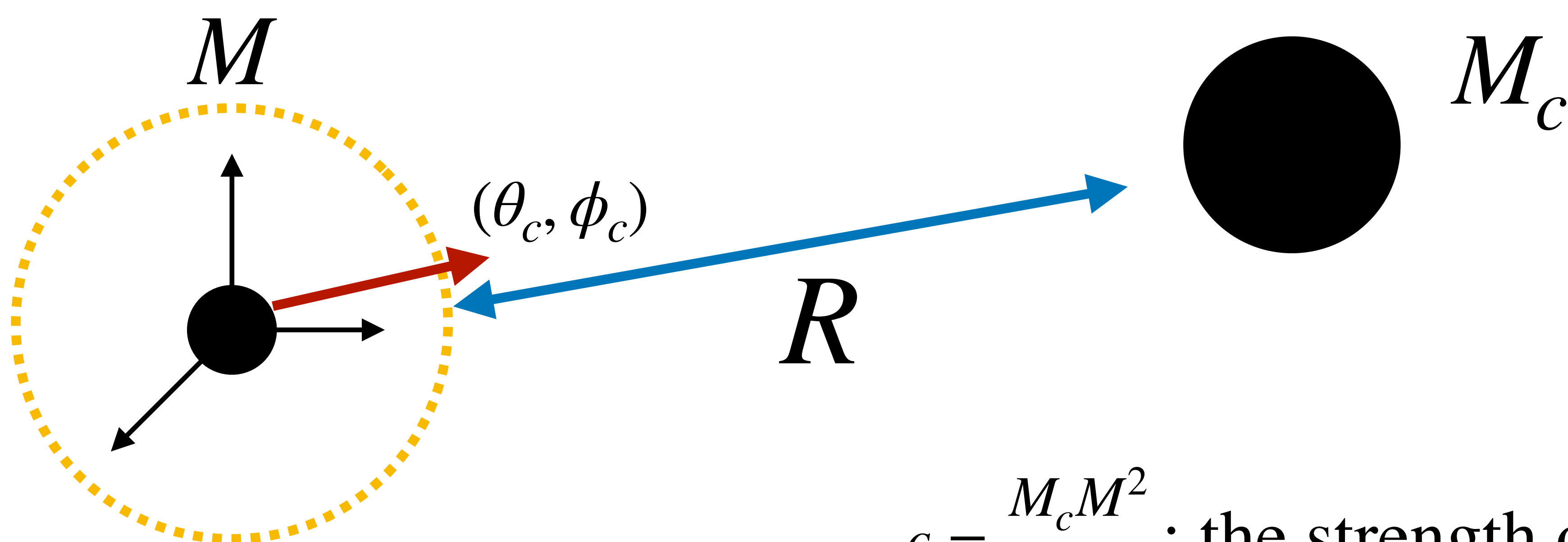
➡ Numerical simulation is good approach.

- For simplicity, we focus on static tidal field.
- Weak tidal : consistency check with perturbation theory
- Strong tidal : threshold of the tidal disruption





Tidally deformed BH



$\epsilon = \dfrac{M_c M^2}{R^3}$: the strength of tidal force

tidal effect

$$ds^2 = ds^2_{\rm BH} + \sum_m \left(\frac{r}{M}\right)^2 \frac{8\pi\epsilon}{\underline{5}} Y^*_{2m}(\theta_c, \phi_c) Y_{2m}(\theta, \phi)\left(f^2 dt^2 + dr^2 + (r^2 - 2M^2) d^2\Omega\right) + \cdots$$

with Regge Wheeler gauge

- We solve the KG eq. on this metric.

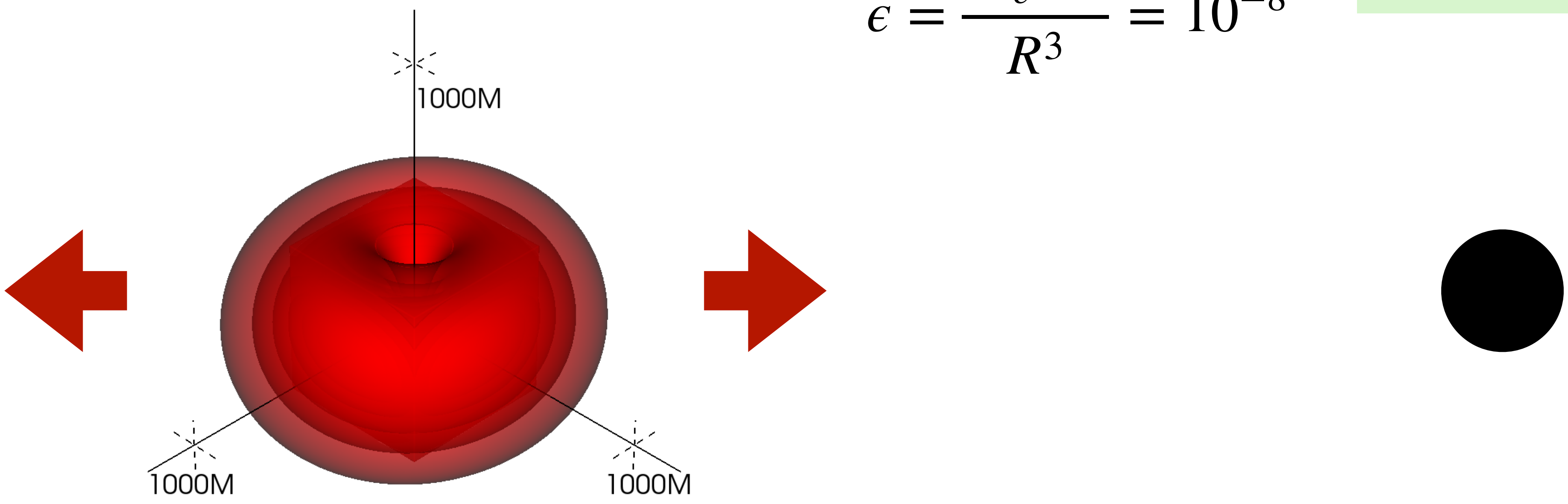
$$\left(\Box - \mu^2\right)\Phi = 0$$

$$f = 1 - \frac{2M}{r}$$

$$\Phi\,|_{t=0} = A_0 r M \mu^2 e^{-rM\mu^2/2} \cos(\phi - \mu t) \sin\theta$$

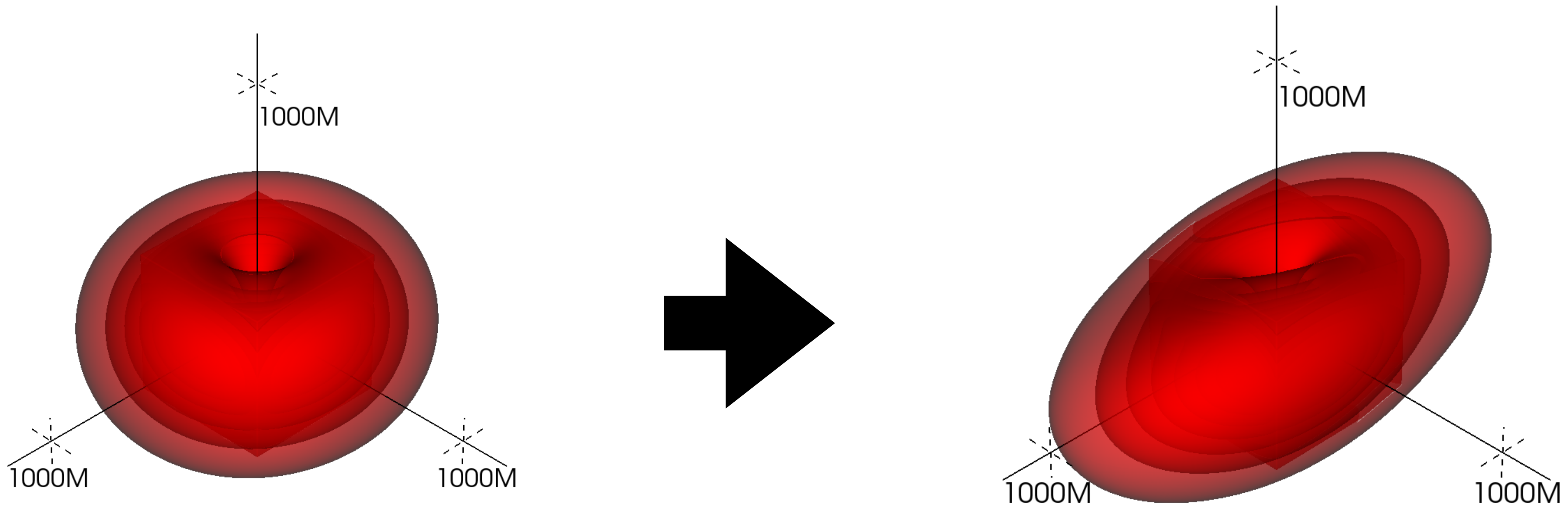
cf: $R = 10^4 M$
$M_c = 10^4 M$

$$\epsilon = \frac{M_c M^2}{R^3} = 10^{-8}$$



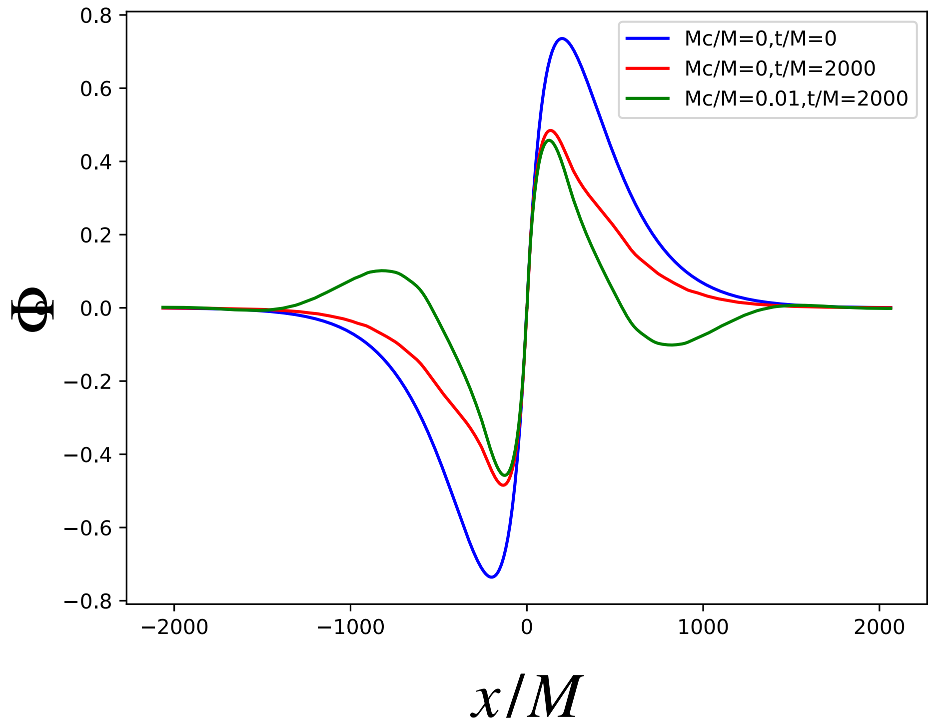
Simulation 1 : Weak tidal case

Weak tidal case

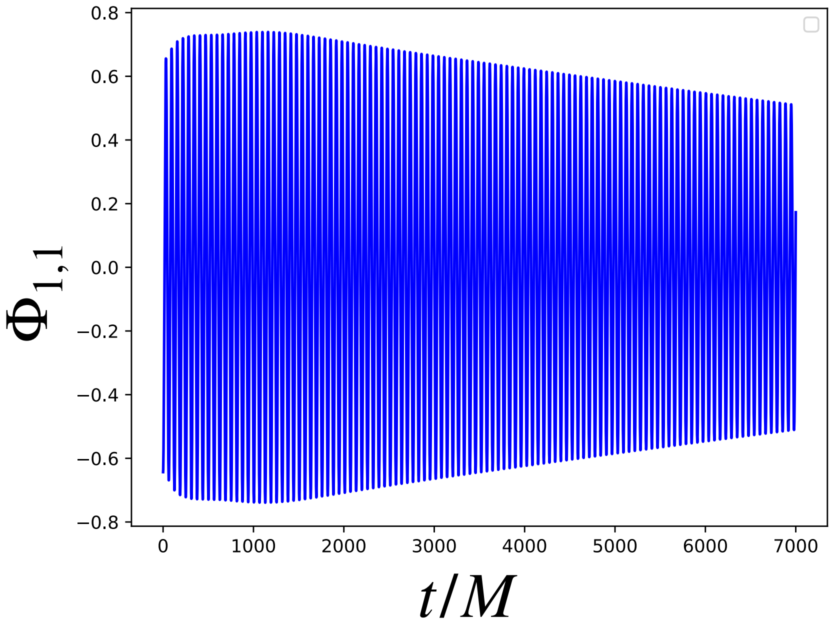


Weak tidal case

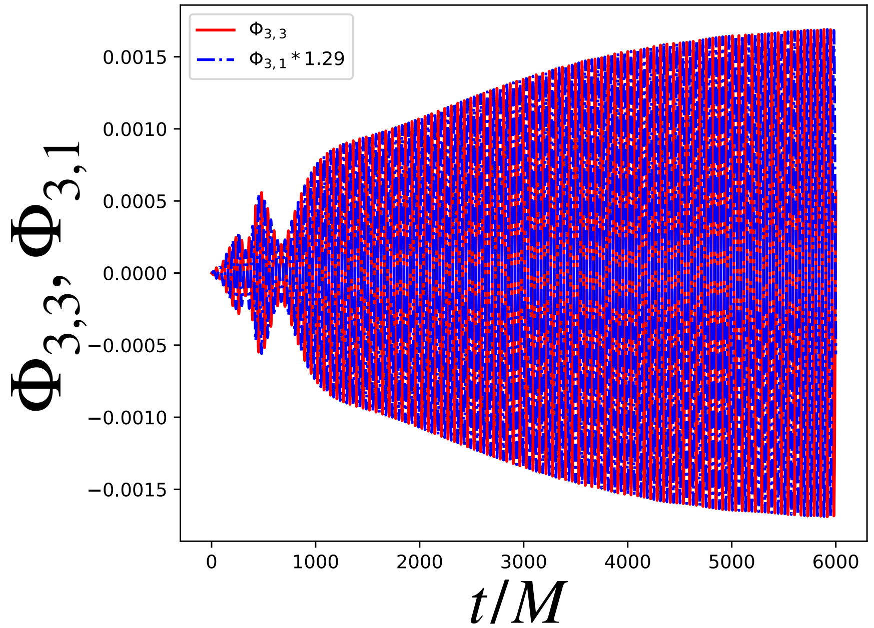
- Excitation of overtone mode.
  - $n = 3,4$ modes are excited.
  - consistent with perturbation theory of QM. (Up to a few factor)



- Excitation of higher l mode.



$\Phi_{3,3} \simeq 1.29\Phi_{3,1}$

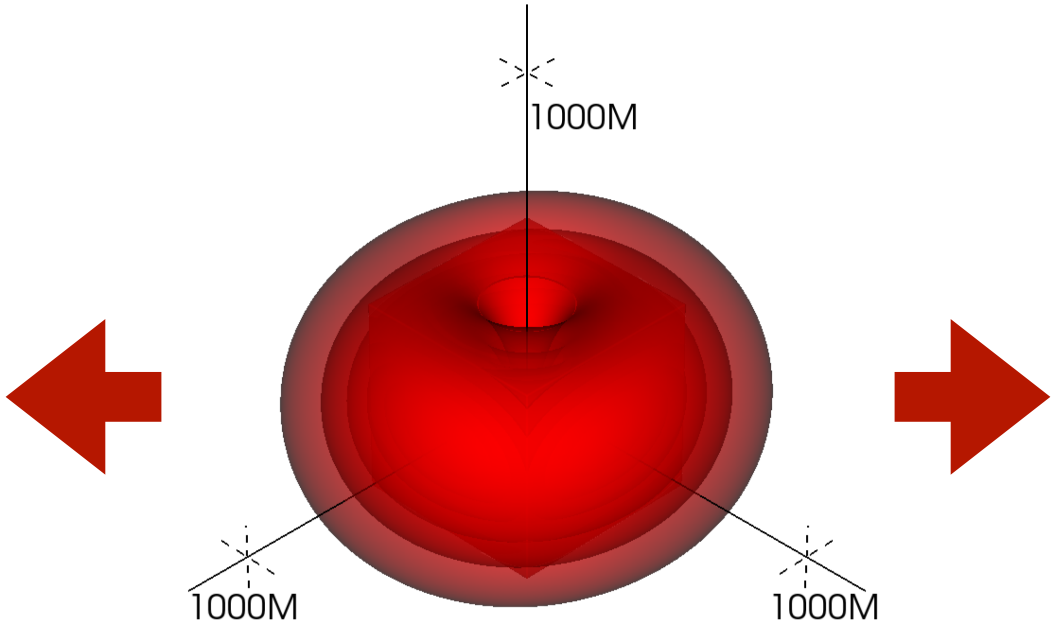


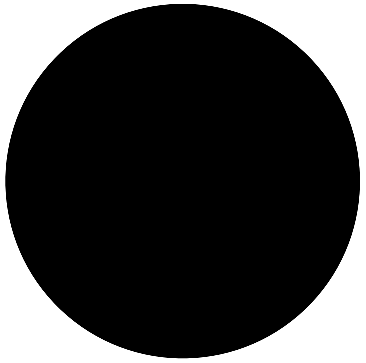
➡ Strong gravitational wave emission is expected.

$$\epsilon = \frac{M_c M^2}{R^3} = 10^{-7}$$

cf: $R = 10^4 M$

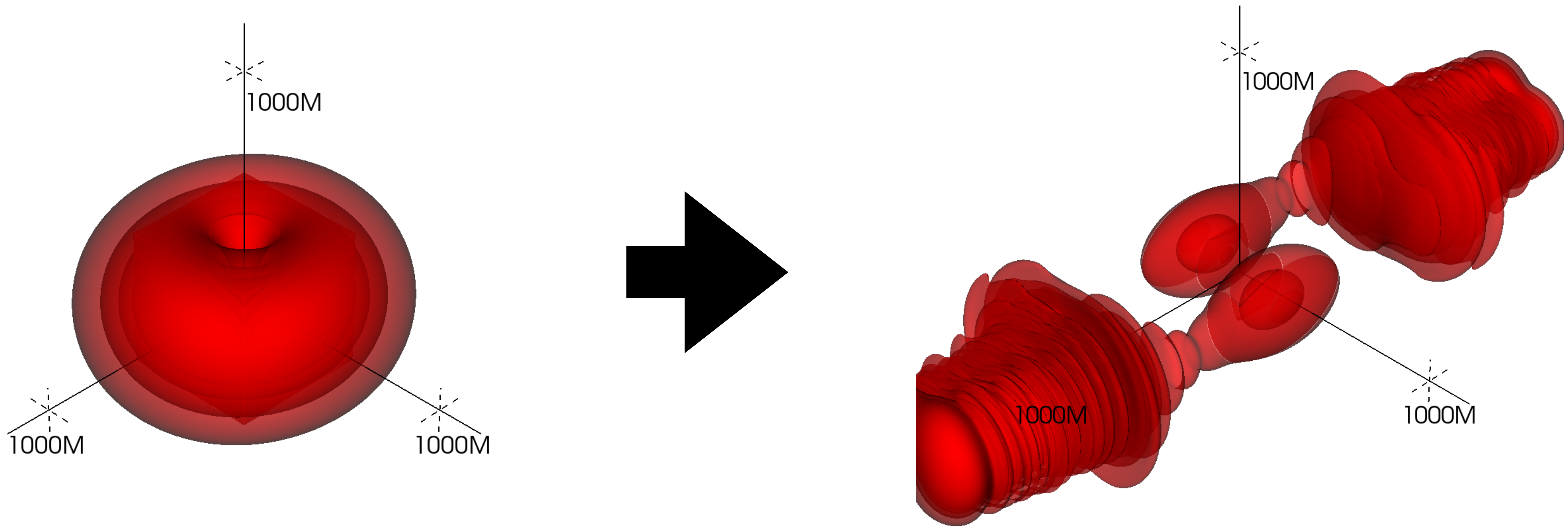
$M_c = 10^5 M$





Simulation 2 : Strong tidal case

Strong tidal case

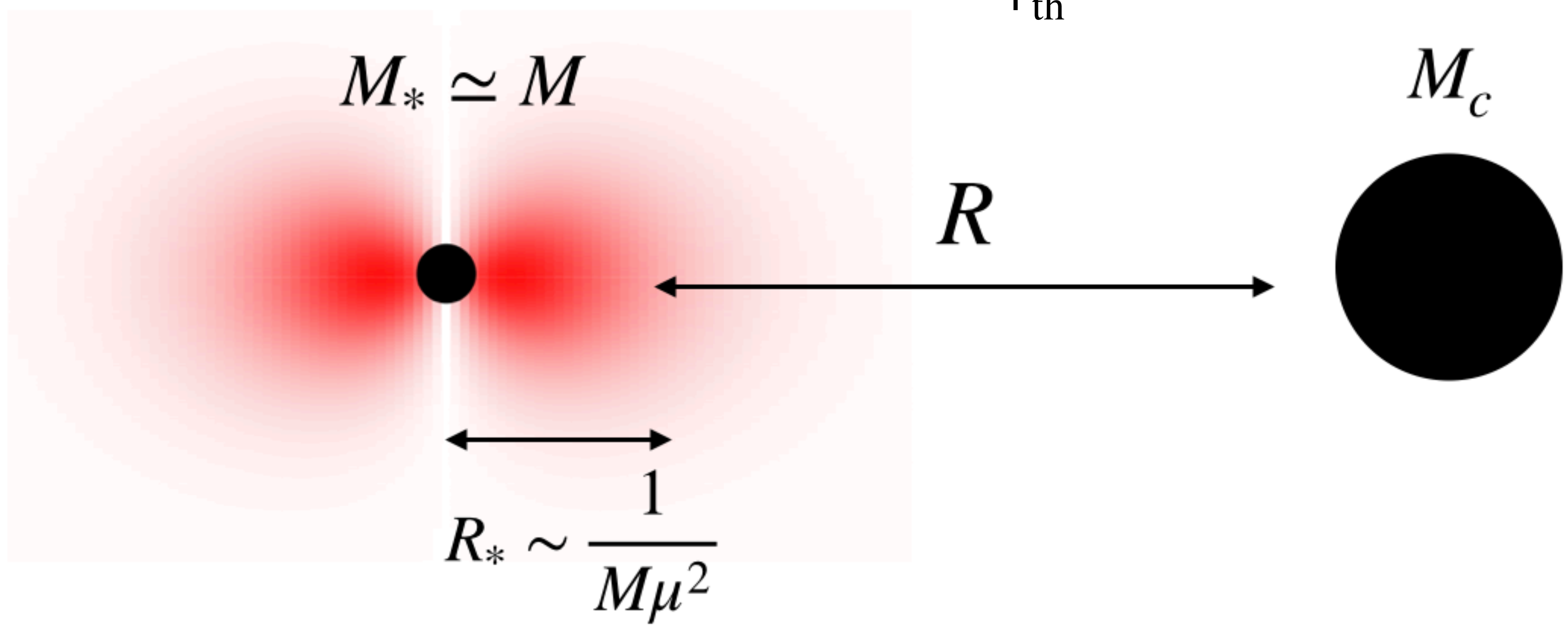


Strong tidal case

- Tidal disruption

cf: Roche limit

$$\frac{M_*^2}{R_*^2} \sim \frac{R_*}{R}\frac{M_c M_*}{R^2} \quad \Rightarrow \quad \left.\frac{M_c M^2}{R^3}\right|_{\rm th} \sim (M\mu)^6 \begin{cases} 10^{-6} \ (\text{ for } M\mu = 0.1 \ ) \\ 6\times 10^{-5} \ (\text{ for } M\mu = 0.2 \ ) \end{cases}$$

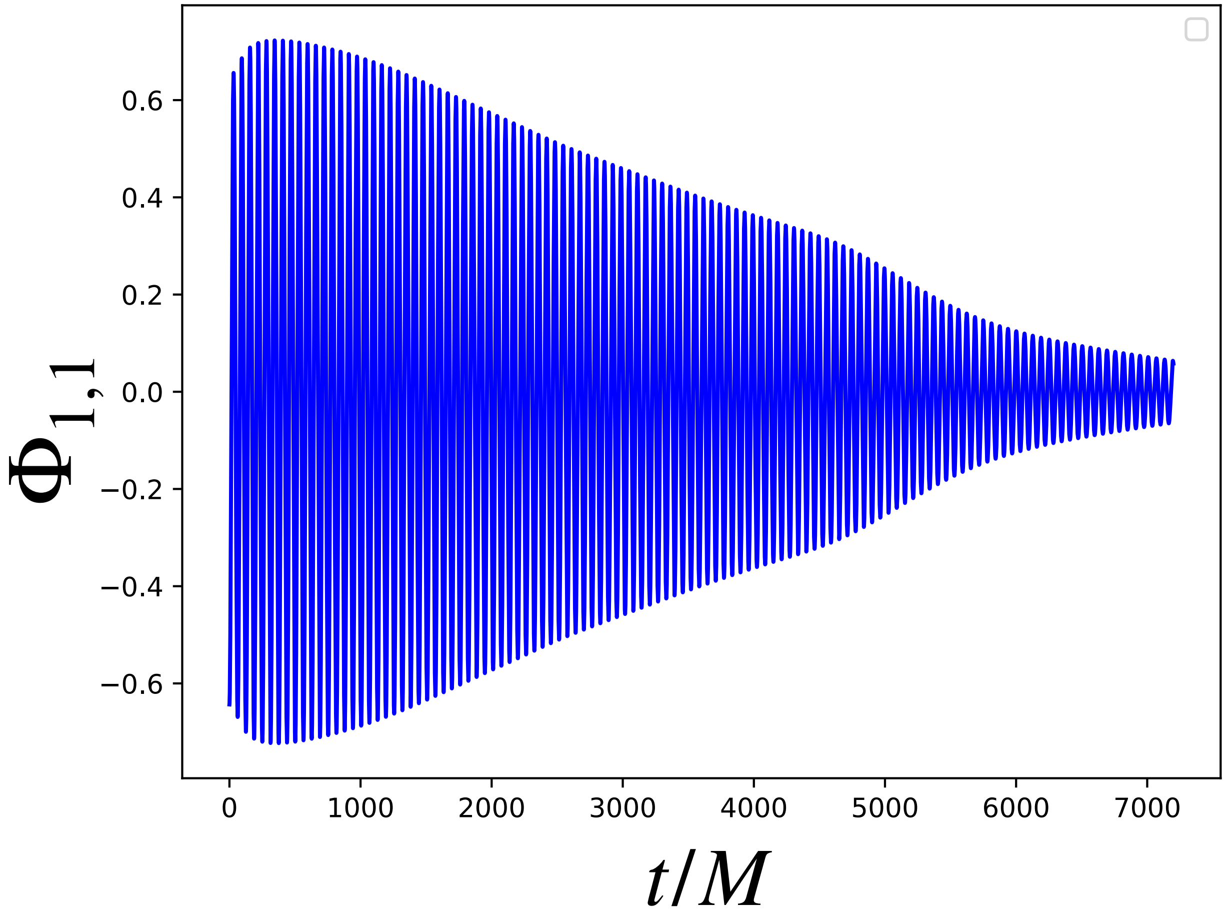


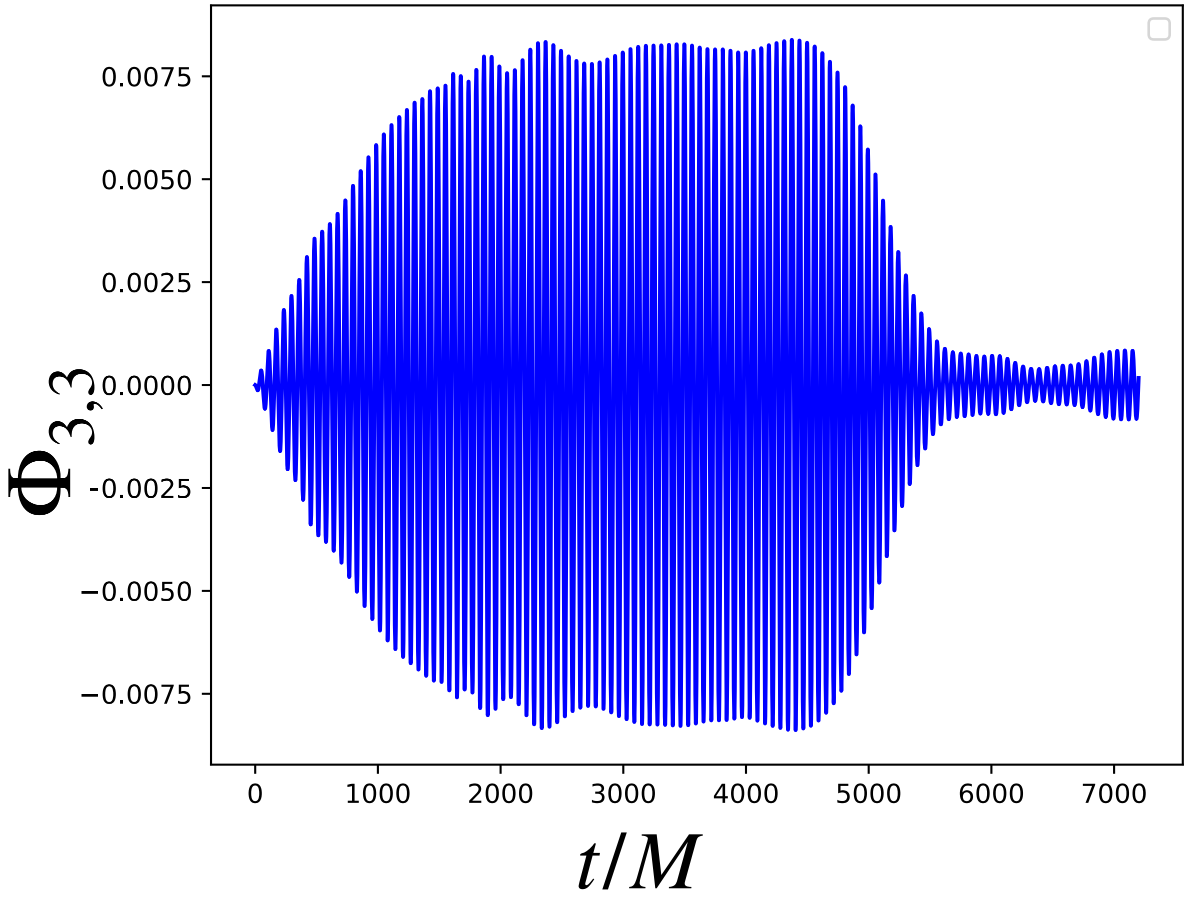
- Numerical result

$$\epsilon_{\rm th} = \left.\frac{M_c M^2}{R^3}\right|_{\rm th} \sim \begin{cases} 10^{-8} \ (\text{ for } M\mu = 0.1 \ ) \\ 2\times 10^{-7} \ (\text{ for } M\mu = 0.2 \ ) \end{cases} \sim \frac{1}{250}(M\mu)^6$$

Strong tidal case

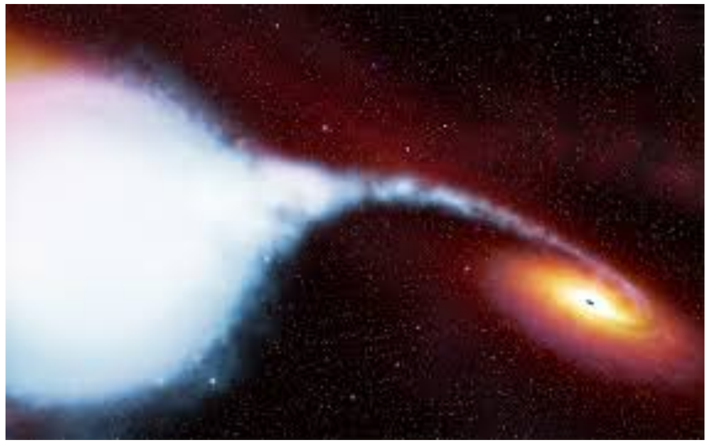
- After higher mode is excited, the cloud is disrupted.





Astrophysical application (In progress)

cf: $t_s \sim M(M\mu)^{-9}$

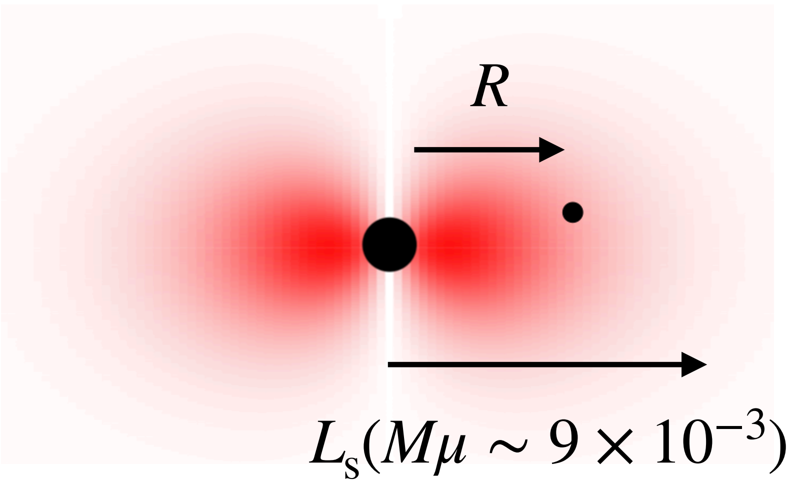


- Cygnus X-1 (J.A.Orosz et al (2011))
  - $M_{\rm BH} \sim 15 M_\odot$
  - $M_c \sim 20 M_\odot$ $\Rightarrow$ $\epsilon \simeq 5 \times 10^{-19}$
  - $R \sim 3 \times 10^{10}$ m

$\Rightarrow$ Scalar cloud with $M\mu \lesssim 2 \times 10^{-3}$ is disrupted.

- Sgr A* (S2) (R.Abuter et al (2018))
  - $M_{\rm BH} \sim 4 \times 10^6 M_\odot$
  - $M_c \sim 20 M_\odot$ $\Rightarrow$ $\epsilon \simeq 2 \times 10^{-15}$
  - $R \sim 1400 M_{\rm BH}$

$\Rightarrow$ Corresponding mass scale : $M\mu \lesssim 9 \times 10^{-3}$



* This is beyond our approximation.

Summary

- We considered tidal effect on scalar cloud.
- We investigate the time evolution of the cloud under tidal force.
  - Higher multipole mode is excited.
    - Strong gravitational wave emission is expected.
  - Tidal disruption

$$\epsilon_{\mathrm{th}} \sim \frac{1}{250}(M\mu)^6$$

- Future work
  - Time dependent tidal force
  - Gravitational wave from deformed cloud